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A Parametric Frequency Increased Power Generator for Scavenging Low Frequency Ambient Vibrations

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Abstract

This paper presents the design, fabrication, and testing of a miniature electromagnetic inertial power generator for scavenging low-frequency non-periodic vibrations. A bi-stable mechanical structure is used to initiate high-frequency mechanical oscillations in an electromagnetic scavenger. Because of the fixed internal displacement of this architecture, power density is improved and miniaturization can be achieved, while accommodating large amplitude vibrations. The fabricated device generated a peak power of 288μW and an average power of 5.8μW from an input acceleration of 9.8m/s^2 at 10Hz. The device operates over a frequency range of 20Hz. The internal volume of the generator is 2.1cm^3 (3.7cm^3 including casing), half of a standard AA battery.

Keywords: Energy scavenging; Energy harvesting; Power generator; Frequency up-conversion

1. Introduction

Looking around, we seem to be surrounded by portable electronics, to the extent that computing is becoming ubiquitous. Rapid advances in wireless microelectromechanical systems (MEMS) over the past several decades have resulted in microsystems with unprecedented performance, while the amount of energy needed to operate these devices has been decreasing at a steady pace. These trends have sparked an interest, over the past few years, to develop novel power sources, capable of extracting energy from the device's surroundings, in order to fulfill their energy needs. Energy scavenging, or energy harvesting, is capable of enabling a variety of new applications from a technical standpoint, while reducing the cost and increasing the feasibility of applying wireless microsystems to others.

A number of ambient energy sources have been examined as potential candidates for energy scavenging applications, such as solar power, temperature gradients, and pressure differentials. However, one of the most ubiquitous is ambient motion. A great deal or research has already been performed to develop new and effective vibration scavenging technologies [2]. However, the main methodology employed in the developed generators to date is to utilize a resonant system that is capable of scavenging high frequency, periodic vibrations, such as the ones produced by electric motors and various other machines. However, this technology cannot be applied in many, if not

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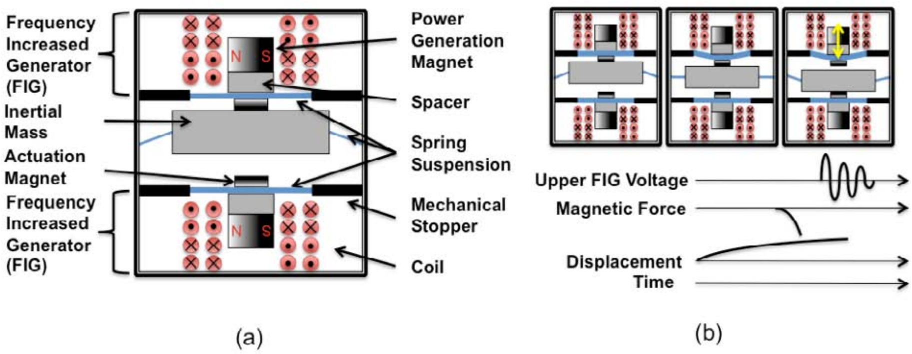


Fig 1. a) Parametric Frequency Increased Generator (PFIG). b) Theory of operation - the generator is depicted at three instances of time during an incident displacement.

a majority, of the applications suitable for energy scavenging because the kinetic energy found in those environments is non-periodic and much less frequent. Examples include power sources for wearable and implantable devices, environmental monitoring systems, agricultural applications, and security and military uses.

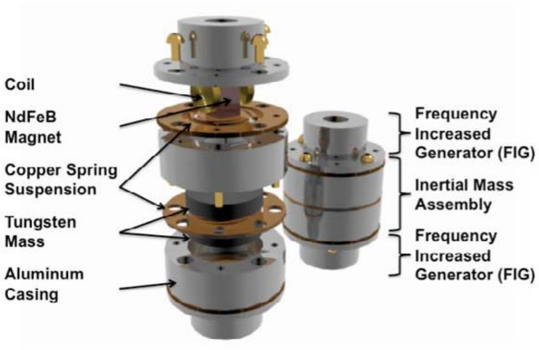
This paper presents the design, fabrication, and testing of a miniature electromagnetic inertial power generator for scavenging low-frequency non-periodic vibrations. It implements the Parametric Frequency Increased Generator (PFIG) architecture, which was previously demonstrated using a bench-top prototype [1].

2. Motivation and Design

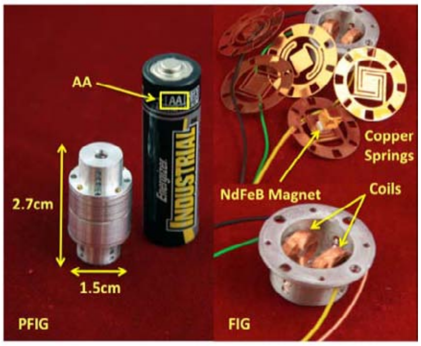
Typical inertial power generators employ a suspended mass to perform work against a damping transduction force as it moves relative to the generator casing. Inertial generators are usually operated at their resonant frequency in order to take advantage of the inherent mechanical amplification due to the device's quality factor. While this technique is very effective for periodic vibrations with small amplitudes, it becomes inefficient when the ambient vibrations do not have a well-defined period and when their amplitude exceeds the internal displacement limit of the generator.

A novel non-resonant inertial generator architecture was introduced and demonstrated using a bench-top macro scale prototype [1] and is shown in Fig 1a. The Parametric Frequency Increased Generator (PFIG) is designed to accommodate the large amplitudes associated with low-frequency vibrations, and because it works in a non-resonant fashion, the PFIG is able to operate over a wide band of frequencies. The PFIG utilizes a large inertial mass to couple kinetic energy, from the ambient, inside the generator structure, and pass a portion of it to one of two Frequency Increased Generators (FIGs), which then convert this mechanical energy to electrical via electromagnetic induction. Two FIGs are placed on either side of the inertial mass, oriented to face each other. Attached to the bottom of the FIG spring is an NdFeB magnet for power generation, while on top, a smaller magnet is used to generate a magnetic force in order to latch the FIG and the inertial mass together. The operation of the PFIG is outlined in Fig 1b. The generator operates such that the inertial mass snaps back and forth between the two FIG generators, attaching magnetically. As the inertial mass moves, it pulls the FIG spring along. When the inertial mass approaches the opposing FIG, the magnetic force of attraction begins to increase. As the forces on the FIG/inertial mass system overwhelm the holding magnetic force, the inertial mass detaches and is pulled to the opposing FIG. The freed device now resonates at its high natural frequency converting the stored mechanical energy in its spring, to electrical. This process is subsequently repeated in the opposite direction.

Another factor contributing to the decrease in efficiency associated with scavenging energy from low-frequency vibrations, using piezoelectric and electromagnetic transductions, is that the electromechanical coupling, or damping force, is proportional to velocity. In other words, the electromechanical coupling will be weaker as the frequency (and thus velocity) drops. The FIG component of the generator gets its name from a concept called frequency up-conversion [3], a method to increase the effectiveness of low-frequency scavengers. This is achieved by implementing a mechanical conversion, such that the internal operating frequency of the generator is increased over the input frequency. The damping force is thereby scaled proportionately. The FIGs operate at a frequency that is an order of magnitude higher than the ambient vibration.



(a)



(b)

Fig 2. a) Illustration describing the developed Parametric Frequency Increased Generator (PFIG). b) Photograph of the fabricated PFIG. On the left, the PFIG device is compared with a standard AA battery. On the right, a close-up of one of the FIGs is shown, along with an assortment of etched copper springs.

3. Implementation and Results

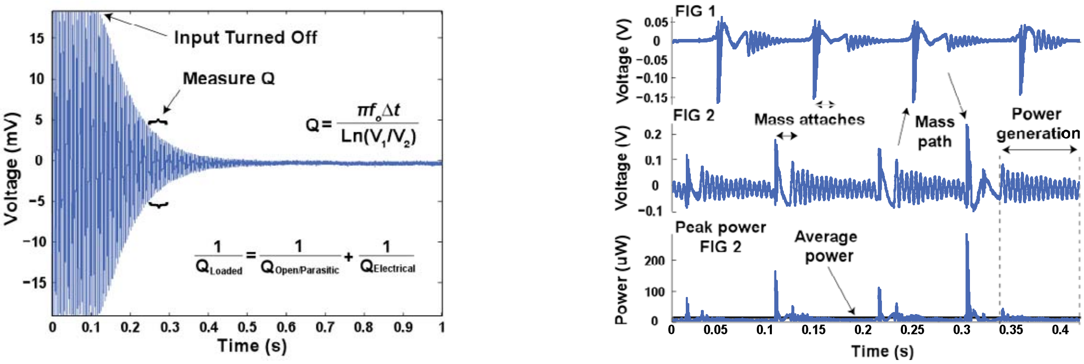
A miniature PFIG generator has been fabricated and tested. Fig 2a shows an illustration of the manufactured device. The generator housing is milled out of aluminum and has a 1mm thick sidewall. It consists of four separate parts, bolted together during assembly, clamping down the spring suspensions in the process. The springs for both the FIG and the inertial mass are fabricated out of 127μm thick copper alloy 110. The copper sheets are mounted on carrier silicon wafers using photoresist, lithographically patterned, and immersion etched in $FeCl_3$ at 45°C. NdFeB magnets are adhered to the FIG springs using cyanoacrylate. Coils are wound from 50μm diameter enameled copper wire, and bonded inside the FIG casing. The inertial mass is made out of two tungsten carbide pieces, machined using electric discharge machining (EDM), and bonded to the spring suspension on either side atop a 1mm spacer. The left side of Fig 2b shows the assembled PFIG next to a standard AA-size battery, while the right side of the figure shows the inside of one of the FIG casings along with an assortment of etched copper springs. Table 1 shows a summary of the various fabricated and measured PFIG parameters.

Initial testing was performed to characterize the FIG devices. Each FIG was mounted on a shaker table and they were actuated at their resonance frequency using an acceleration of 0.1g. By examining the decay of the voltage waveform immediately after the shaker table is switched off, one can determine the parasitic and electrical quality factors by measuring the open circuit and loaded voltage waveforms. A sample voltage trace is shown in Fig 3a to illustrate this process. The PFIG is assembled, and tested at 1g. The minimum frequency at which the generator can be tested accurately is 10Hz due to limitations associated with the vibration test system. Each FIG is loaded with a 240Ω resistor. Fig 3b shows the operation of the PFIG. The top two plots show the voltage generated by each FIG across the load, and the bottom plot shows the instantaneous power from FIG 2. By looking at the voltage waveform it becomes evident where the inertial mass attaches to each FIG, and where the mass detaches and travels to the opposing device. The bandwidth of the PFIG device is determined by the resonant frequency of the inertial mass and its spring suspension. To determine this cutoff, the PFIG input frequency is increased until it stops functioning. It was found that the generator could function up to a frequency of 20Hz. The performance of the PFIG generator is compared with published work designed to operate at 10Hz or less in Table 2.

Table 1. Parametric Generator Summary

FIG Mass	0.25g	FIG Parasitic Q-factor	50	Internal Volume	2.12cm3
FIG Suspension*	614N/m	FIG Magnet	3x3x3mm	Total Volume	3.74cm3
FIG Natural Frequency	208Hz	FIG Displacement Limit	0.5mm	Min. Acceleration	0.9g
FIG Coil Turns	2000	Inertial Mass	9g	Max. Power (1g, 10Hz)	288μW
FIG Coil Resistance	240Ω	Inertial Mass Suspension*	135N/m	Avg. Power (1g, 10Hz)	5.8μW
FIG Electrical Q-factor	97	Actuation Magnet	Dia. 1.15mm, Thick. 0.5mm	Bandwidth	20Hz

*Simulated Value



(a) (b)

Fig 3. a) Decay plot of a FIG connected to a load and actuated at its resonance frequency at 0.1g. This data is used to determine the electromechanical coupling of the FIG as well as the mechanical parasitic losses. b) Oscilloscope trace showing the parametric generator operation from an external acceleration of 1g at 10 Hz.

Table 2. PFIG Performance Comparison

	Input Accel. (g)	Input Freq. (Hz)	Volume (cm^3)	Peak Power (μW)	Avg. Power (μW)	P. Density (μW/cm^3)
Arakawa [4]	0.4	10	0.4	6	-	-
Miao [5]	1.8	10	0.6	-	1.2	2
Saha [6]	0.5	2	12.7	300	-	-
Saha [6]	1	2.5	12.7	1860	-	-
Galchev [1]	1	10	3.68	558.3	39.45	10.7
This Work	1	10	2.12	288	5.8	2.74
*Functional volume of bench-top prototype						

4. Conclusion

This paper reports the design, fabrication, and testing of a miniature PFIG power scavenger that is able to work in environments with low-frequency large displacement vibrations. The fabricated device generated a peak power of 288μW and an average power of 5.8μW at an input acceleration of 1g applied at 10 Hz. The PFIG architecture was previously demonstrated [1] using a bench-top prototype which has now been miniaturized to a size comparable to half of a AA-size battery. While the results still exceed the state-of-the-art in low-frequency scavengers, they did not exceed the performance of the bench top device. Further optimizations are needed in three areas: 1) space optimization of the electromagnetic system – thinner coils, larger magnets, and increased flux density through the coils, 2) better magnetic actuation/latching, because as Fig 3b shows, the two FIG device are not equally effective, and 3) optimized spring design and fabrication, because they are allowing the FIGs to resonate in more than one mode.

Acknowledgements

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